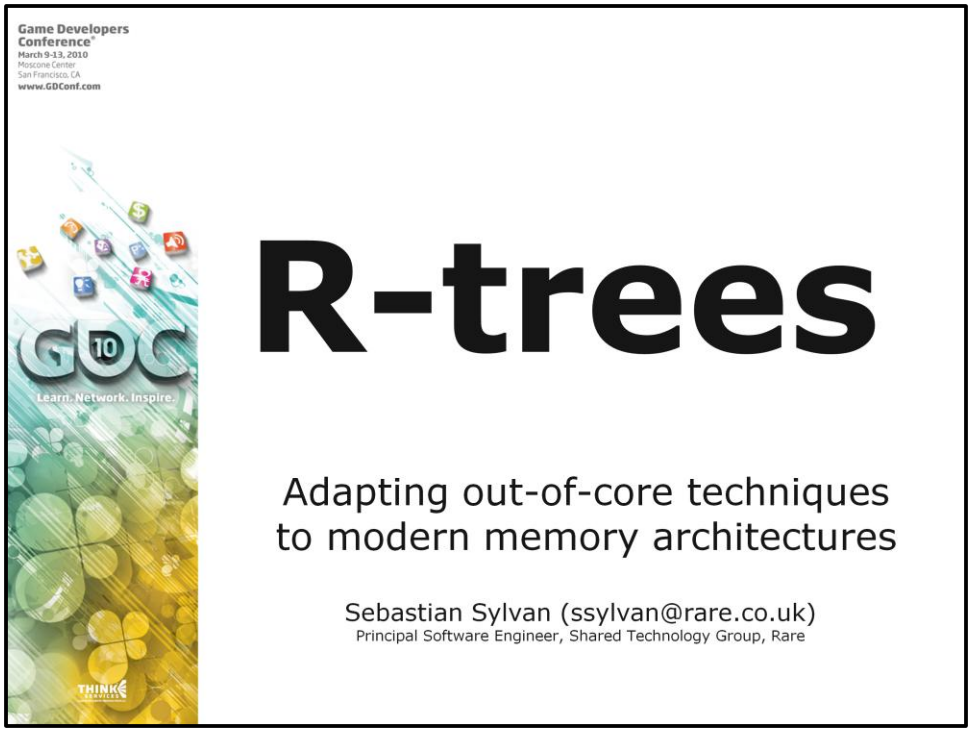
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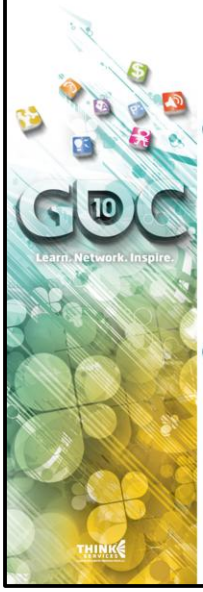
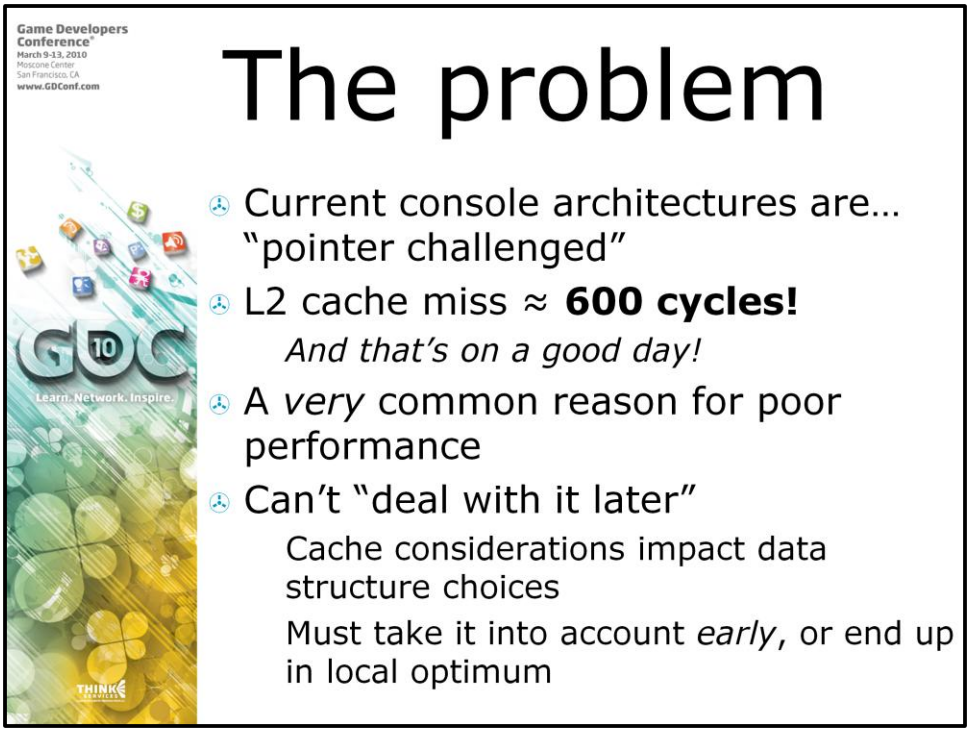
R-trees
Adapting out-of-core techniques to modern memory architectures
Sebastian Sylvan (ssylvan@rare.co.uk)
Principal Software Engineer, Shared Technology Group, Rare



This talk

- Two main themes
  - A neat data structure for spatial organization: R-trees
  - A strategy for finding cache-friendly alternatives to traditional algorithms
- Will use the Xbox 360 for specific examples
  - Mostly applicable to PS3 too (I think! ☺)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The problem
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Current console architectures are… "pointer challenged"
L2 cache miss ≈ 600 cycles!
And that's on a good day!
A very common reason for poor performance
Can't "deal with it later"
Cache considerations impact data structure choices
Must take it into account early, or end up in local optimum

It's very easy to end up in a local optimum if you don't consider cache concerns up front and choose a data structure which has inherently poor cache behaviour (e.g. a KD-tree). You can easily end up optimizing for cache behaviour (compressing nodes, rearranging them in memory), within the constraints of a cache-hostile data structure. If cache misses are a primary concern, it's worth trying a data structure that attacks that problem more directly.

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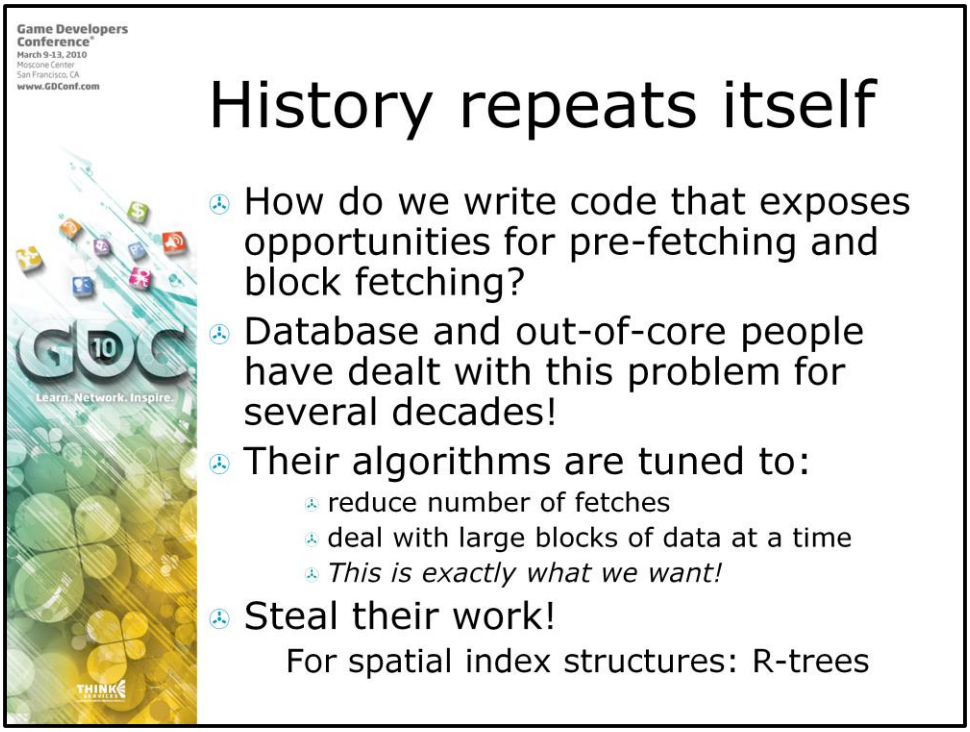
The Solution

- Code shouldn't be written as if memory access was cheap
  - (because it's not)
  - Treat memory access like disk access
- Main tool at our disposal: **dcbt**
  - "Pre-fetch", whenever possible
  - "Block fetch", for unavoidable cache misses
    - Pay one cache miss instead of 8!
  - Opportunities for these rarely occur in the wild without intentional set up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History repeats itself
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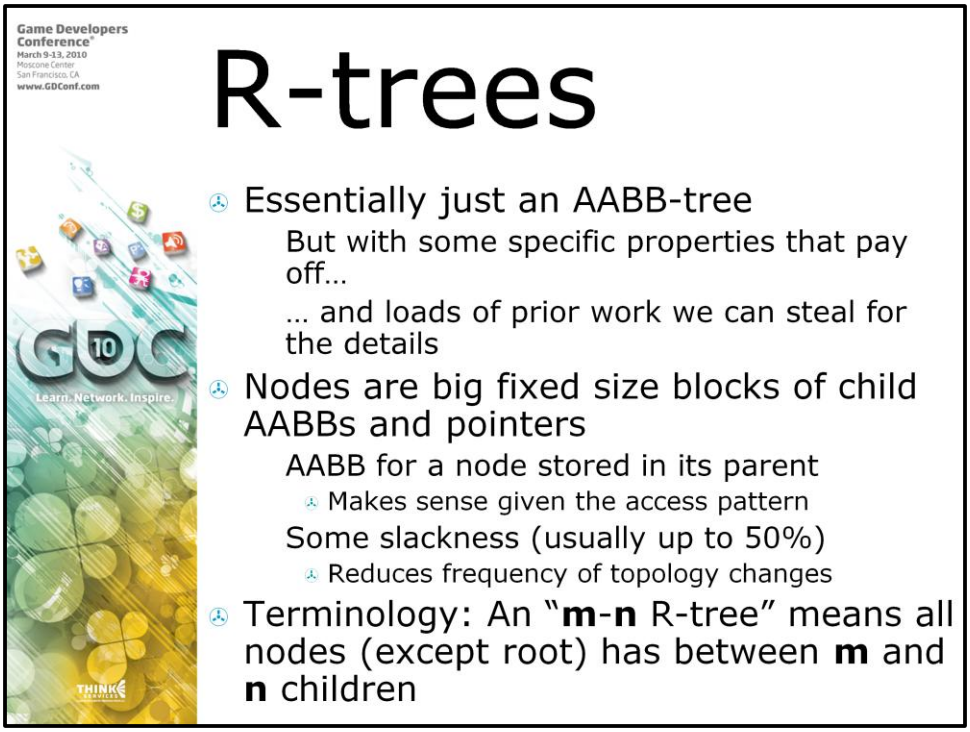
How do we write code that exposes opportunities for pre-fetching and block fetching?
Database and out-of-core people have dealt with this problem for several decades!
Their algorithms are tuned to:
reduce number of fetches
deal with large blocks of data at a time
This is exactly what we want!
Steal their work!
For spatial index structures: R-trees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R-trees
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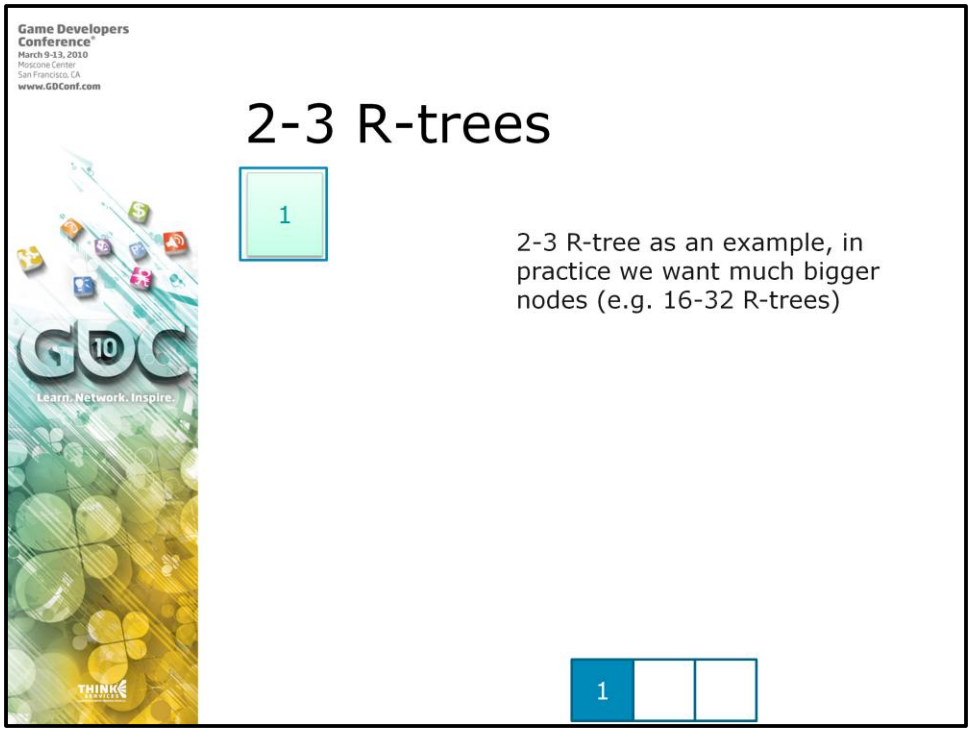
Essentially just an AABB-tree
But with some specific properties that pay off…
… and loads of prior work we can steal for the details
Nodes are big fixed size blocks of child AABBs and pointers
AABB for a node stored in its parent
Makes sense given the access pattern
Some slackness (usually up to 50%)
Reduces frequency of topology changes
Terminology: An "m-n R-tree" means all nodes (except root) has between m and n children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2-3 R-trees
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2-3 R-tree as an example, in practice we want much bigger nodes (e.g. 16-32 R-trees)
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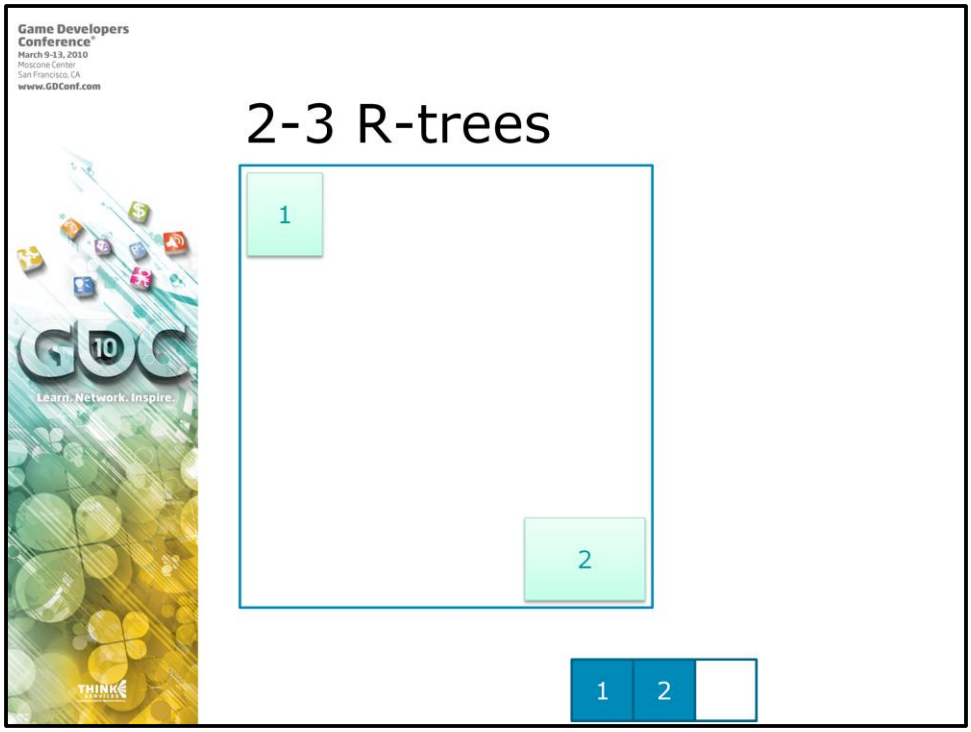
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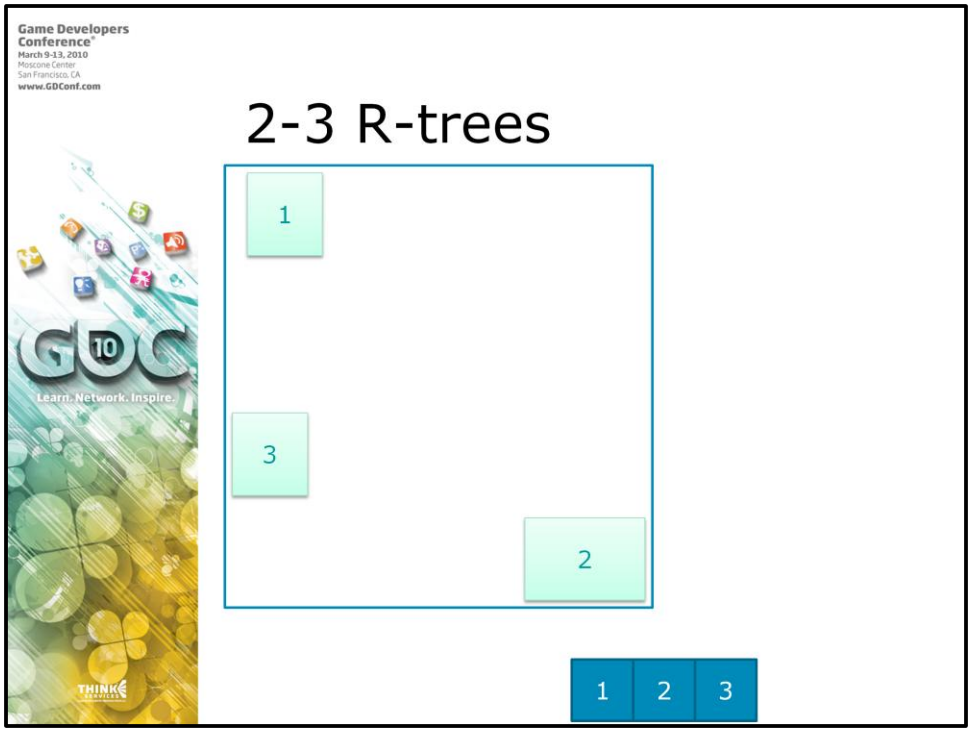
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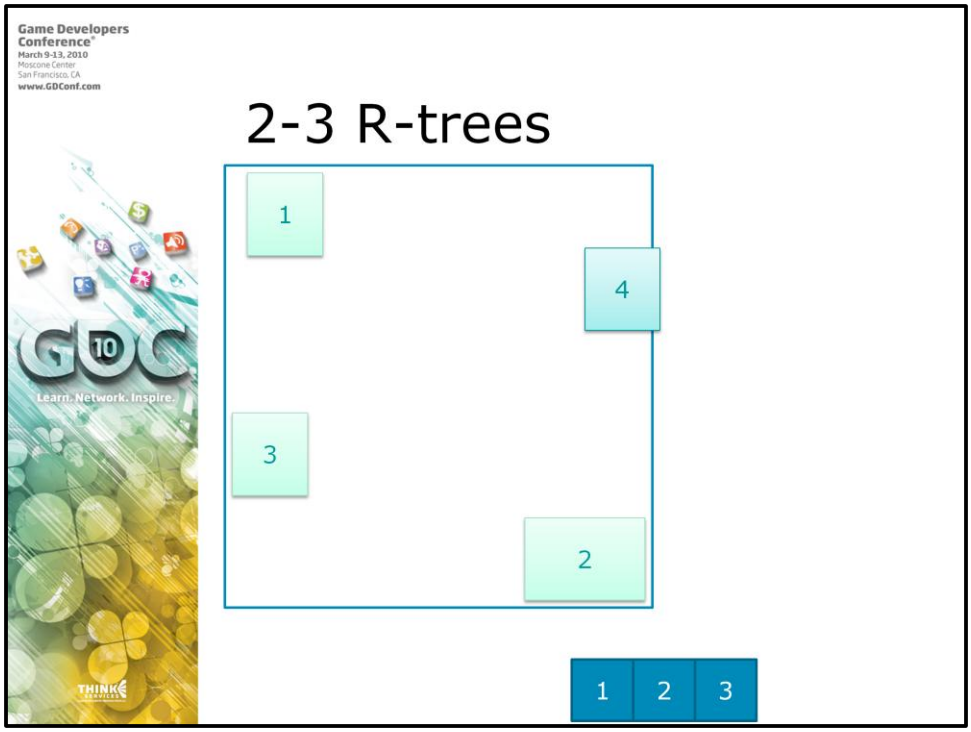
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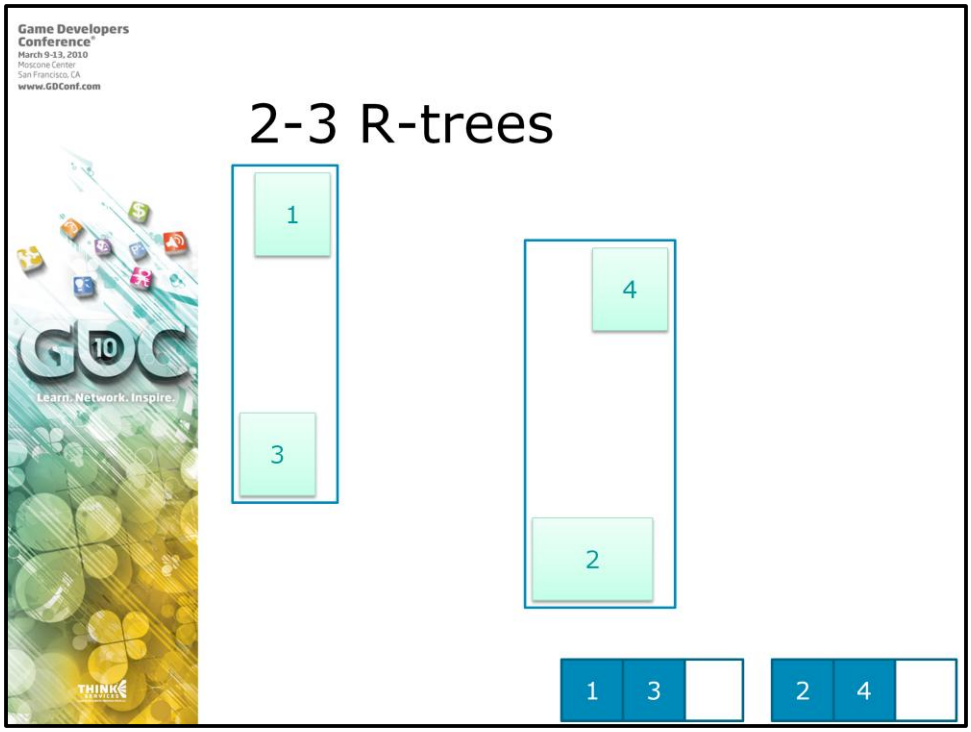
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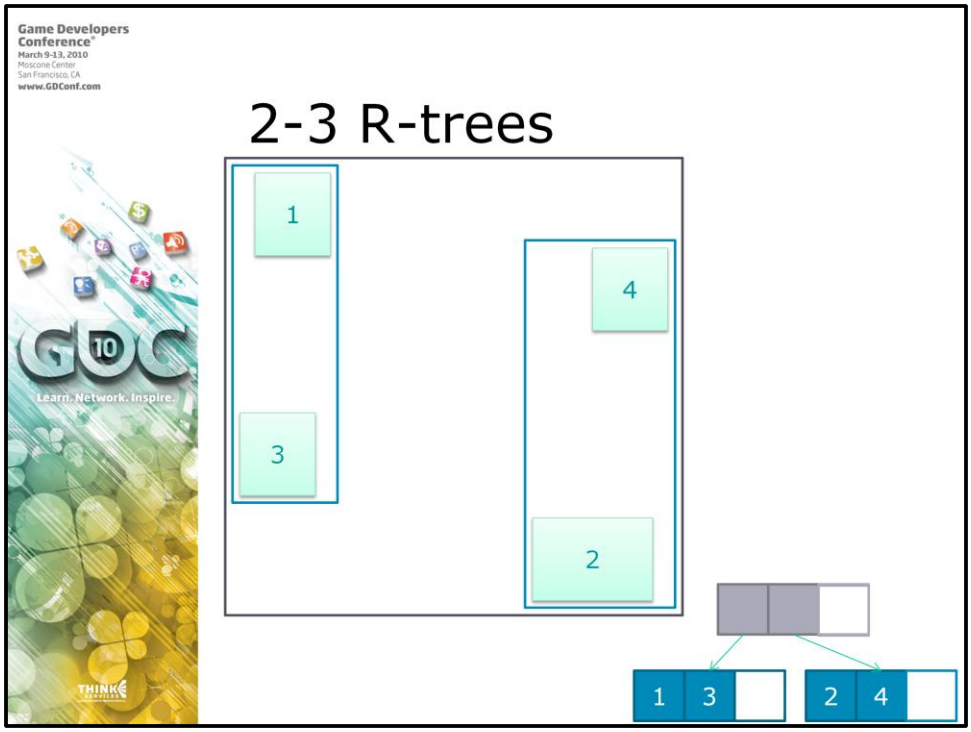
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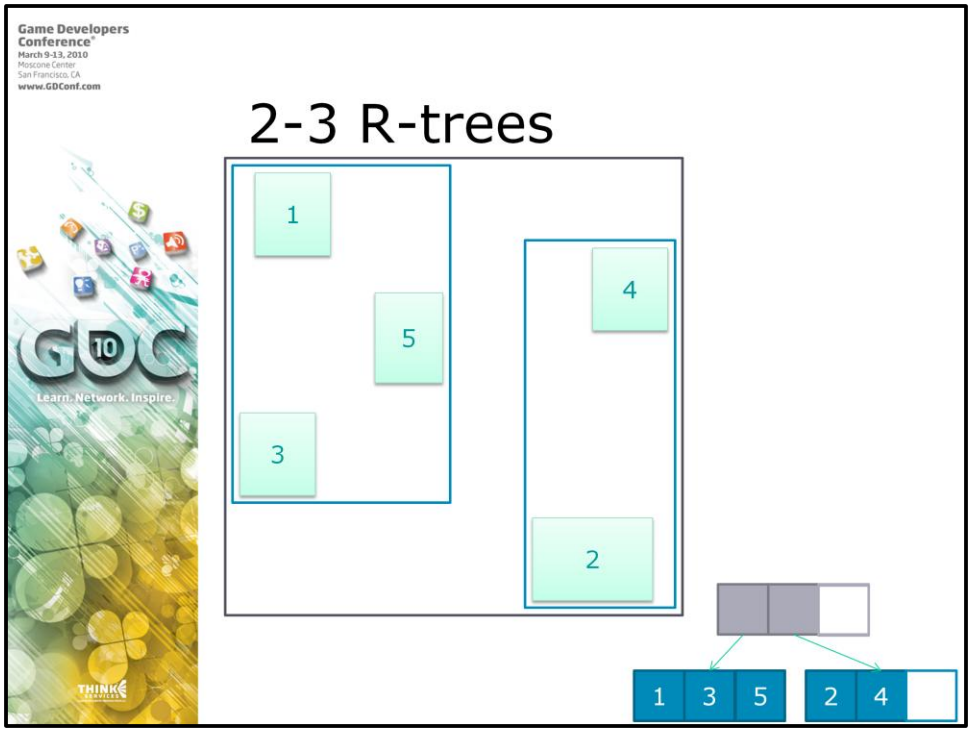
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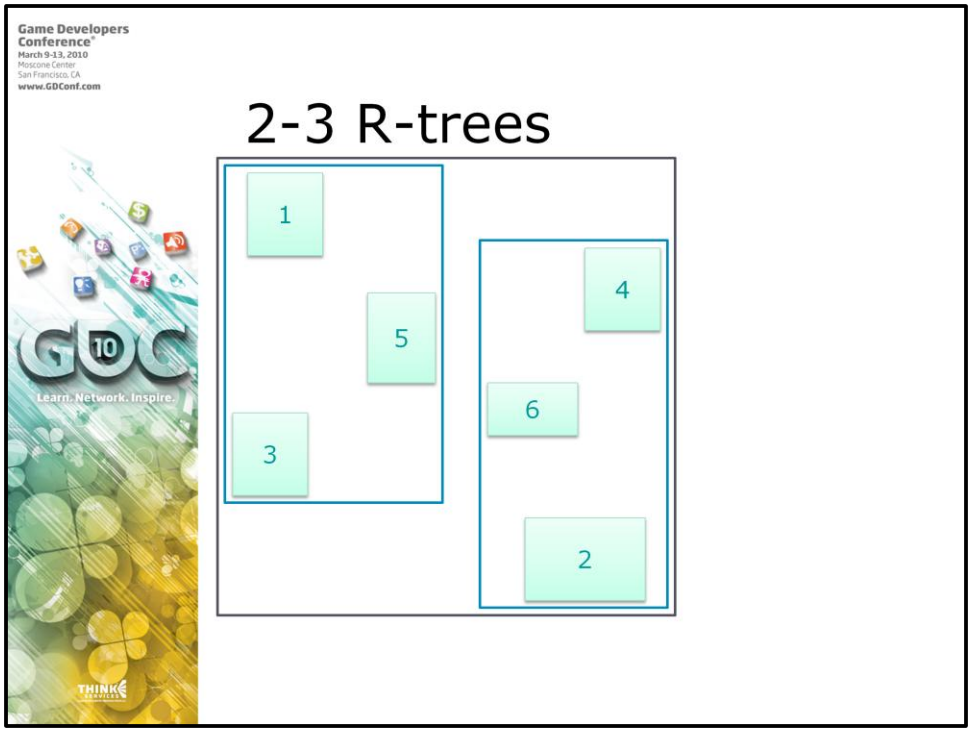
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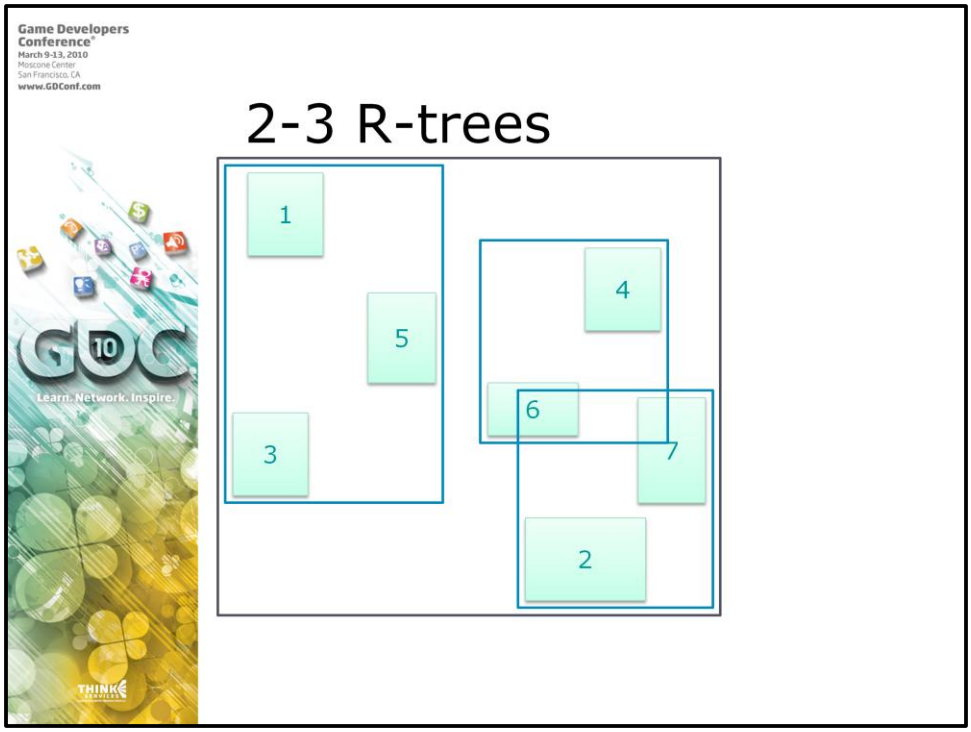
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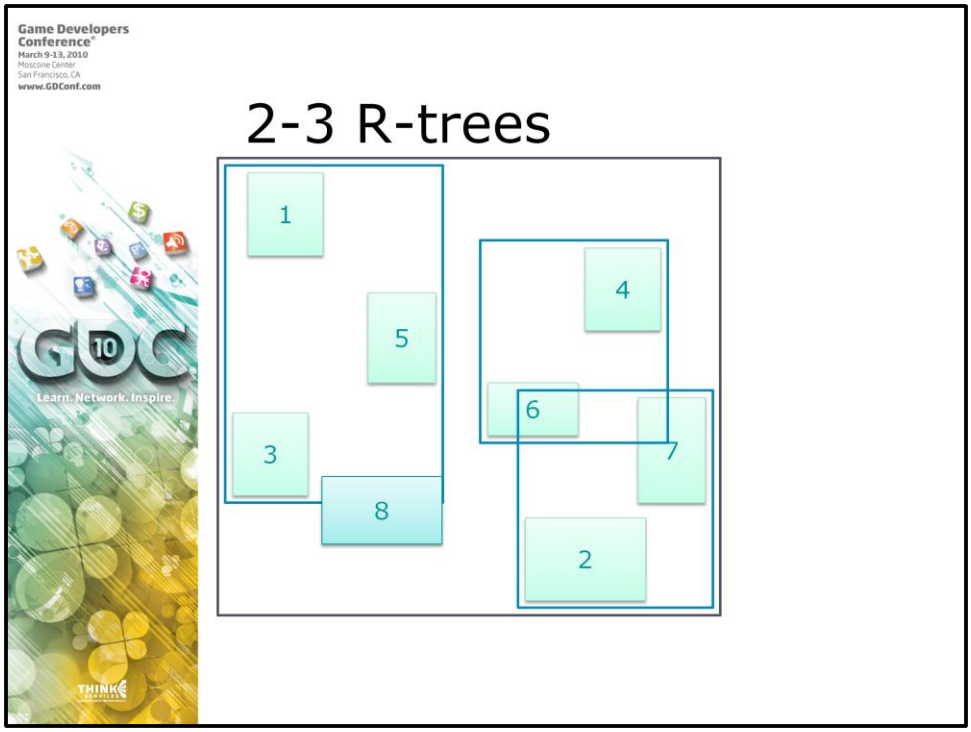
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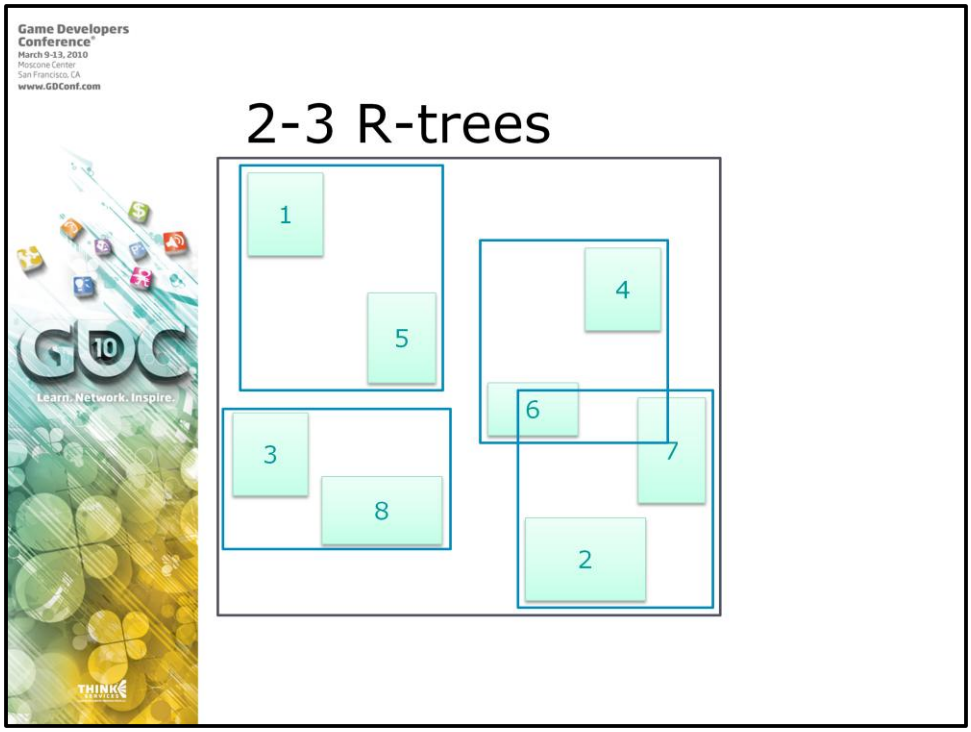
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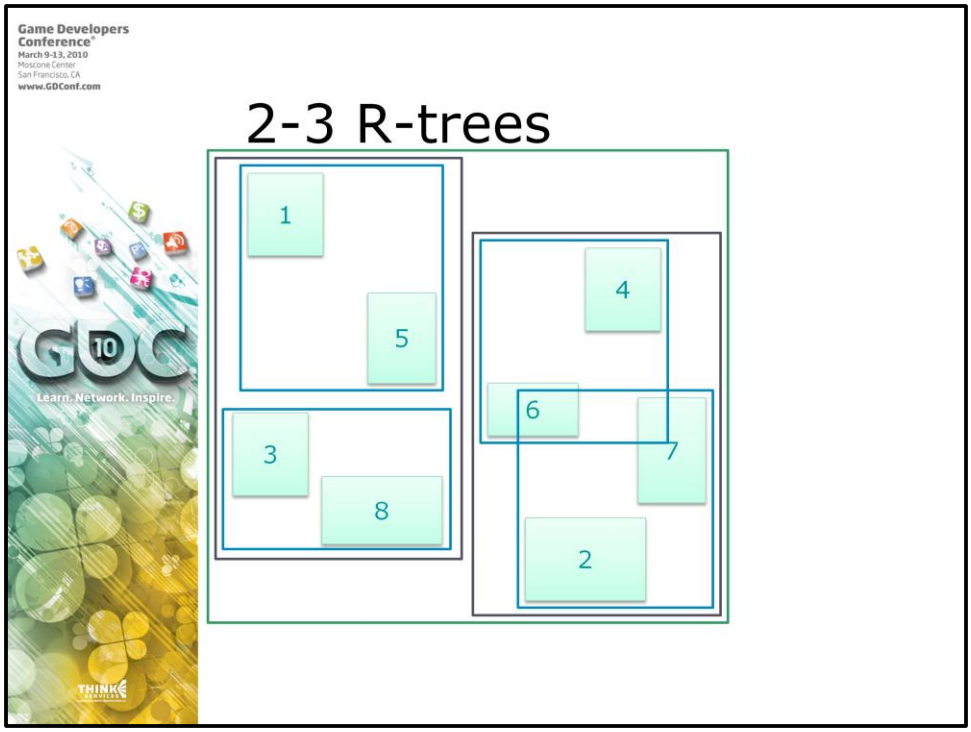
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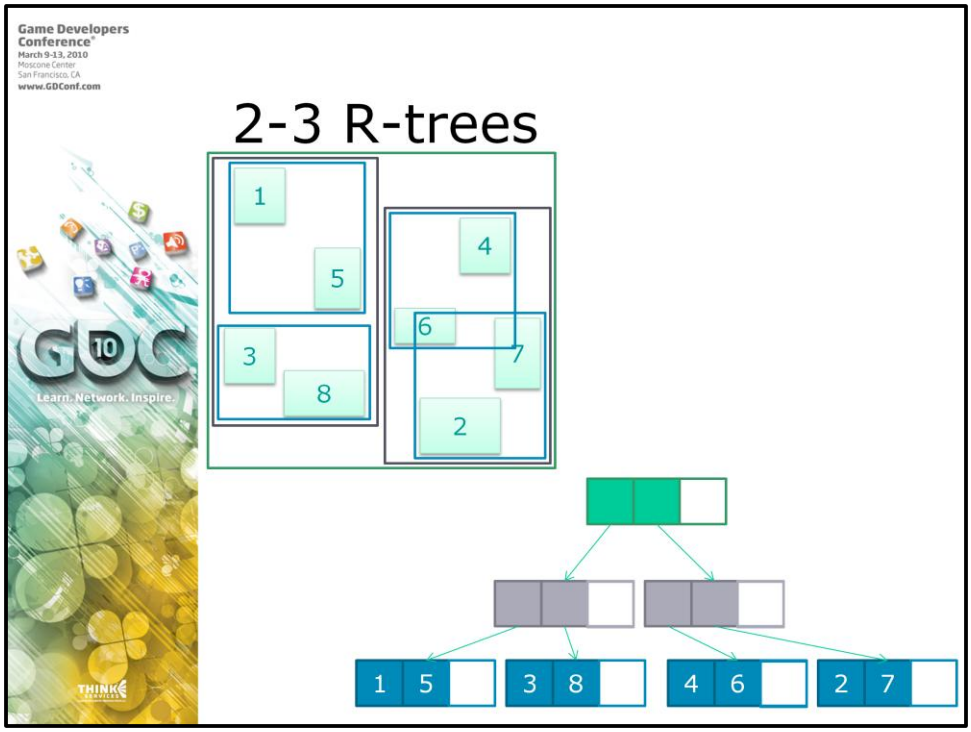
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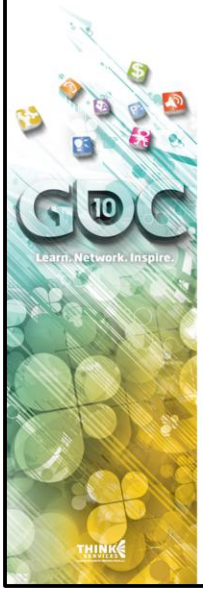
Main Operations on R-trees



- Insert/Delete
  - Saw insert. Pick leaf, split if overflowing, insert new node into parent. (keeps it balanced!)
  - Delete: Remove child from node, fill hole with last child
  - Strictly speaking should handle underflow
    - typically by re-inserting all remaining nodes
    - In practice, delete is often deferred; only remove when node is completely empty
- Range queries (frustum, sphere, AABB etc.)
  - Fairly standard:
    - Check each child's AABB against range
    - if it intersects, recurse until we're at a leaf
    - If it's fully outside range, return nothing
    - If it's fully in range, return all children with no further tests

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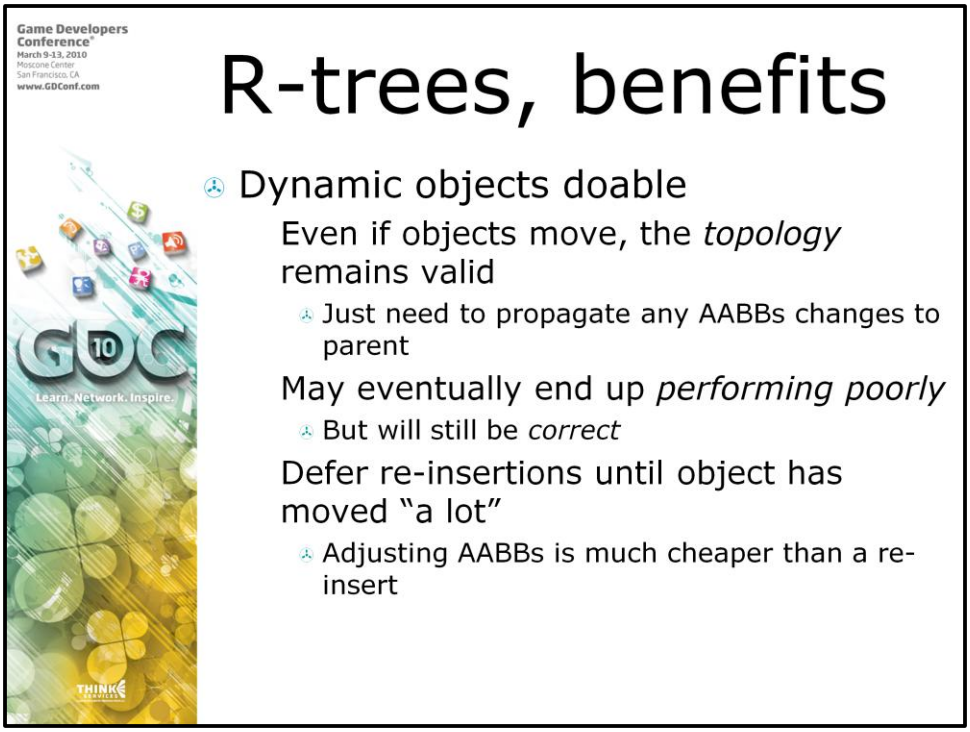
R-trees, benefits

- **Cache friendly data layout**
- No rigid subdivision pattern
- High branching factor
  - shorter depth, fewer fetches, more work within each node
- Prefetching (breadth-first traversal)
  - Stack (depth first): current node can change which node comes next
  - Queue: We know which node is next – so prefetch it!
- Many children per node
  - Unroll tests to hide VMX latency
  - Hides the pre-fetch latency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R-trees, benefits
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Dynamic objects doable
Even if objects move, the topology remains valid
Just need to propagate any AABBs changes to parent
May eventually end up performing poorly
But will still be correct
Defer re-insertions until object has moved "a lot"
Adjusting AABBs is much cheaper than a re-insert

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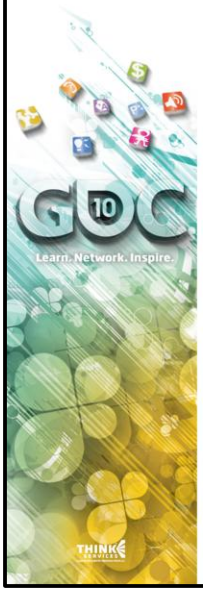
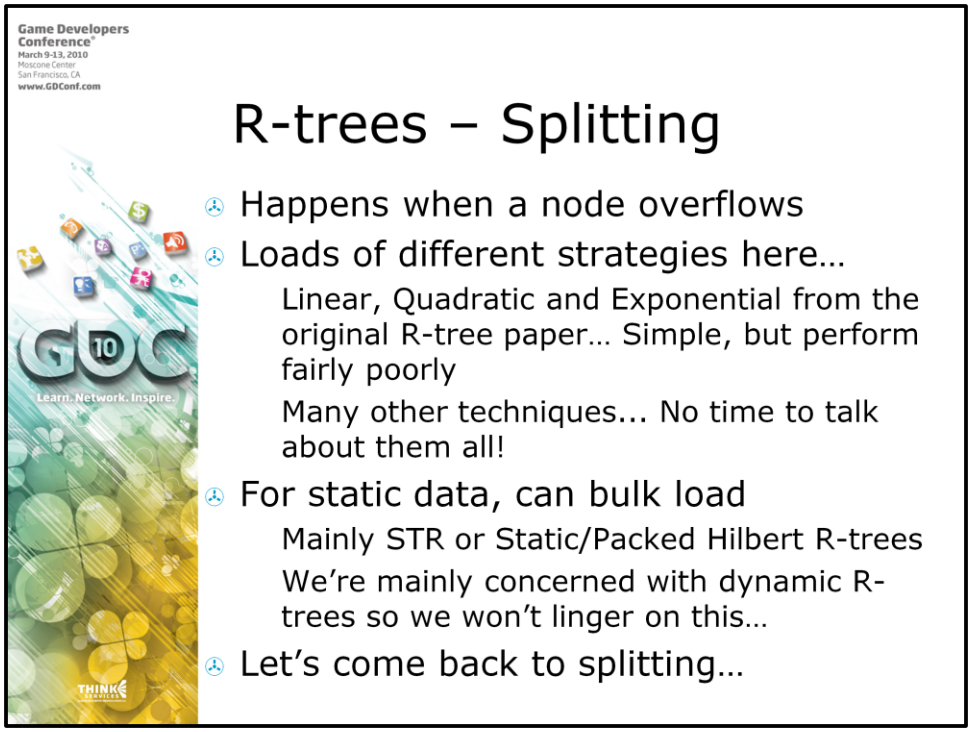
R-trees – Insertion



- How to pick which child node to insert into
- Seems somewhat irrelevant for performance!
  - As long as you do something relatively sensible
  - Splitting seems to have a bigger impact
- Simple strategy:
  - Pick the child node which would be enlarged the least by putting the new object into it



Note: R*-trees and Hilbert R-trees are generally considered the best splitting techniques w.r.t. query performance for dynamic trees. cR-trees tend to do well too…

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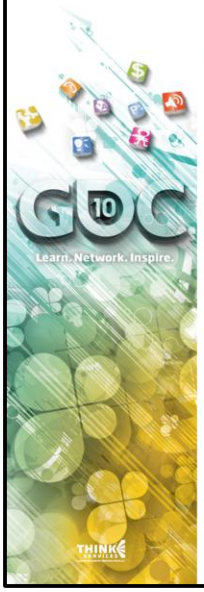
R-trees – Incremental refinement



- Garcia et al.
  "On Optimal Node Splitting for R-Trees"
  - Figured out a fast way to do *optimal* splitting…
  - …but query performance boost was small…
  - *"Thus a second contribution is to demonstrate the near optimality of previous split heuristics"*
    - Ouch!
  - But led to a key insight: *"research should focus on global rather than local optimization"*

Y. J. Garcia, M. A. Lopez, and S. T. Leutenegger. **On optimal node splitting for R-trees**. In *Proceedings of the 24th International Conference on Very Large Databases*, pages 334–344, 1998.

R-trees – Incremental refinement

- Non-local, incremental
- Can do this for e.g. 5% of insertions, or do many iterations whenever we have time to spare
- Can give *better* performing trees than bulk loading!
- Can reshape *any* R-tree into a well-formed one
- If we do this, we can get away with murder for insertions/splitting!

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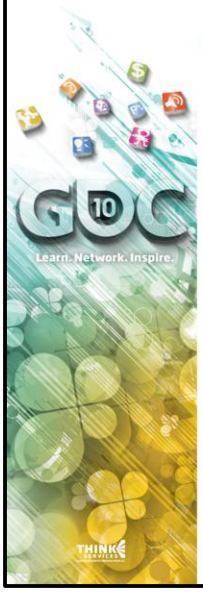

R-trees – Incremental refinement

- Starts at a specific node, ***n*** (typically a leaf)
  - **First, recursively optimize the parent of *n* (unless root)**
    - Helps ensure that we get "good" siblings for the next steps
  - **Then try to merge *n* with an overlapping sibling**
    - Improves space utilization
  - **Else, for each overlapping sibling to *n*, take the union of its and *n*'s children, and then split that**
    - Redistributes child nodes between siblings, improving overlap, empty space etc.

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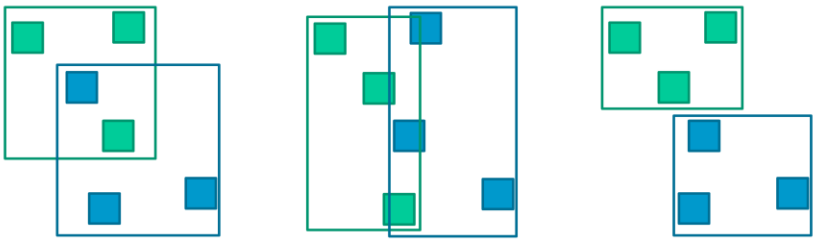
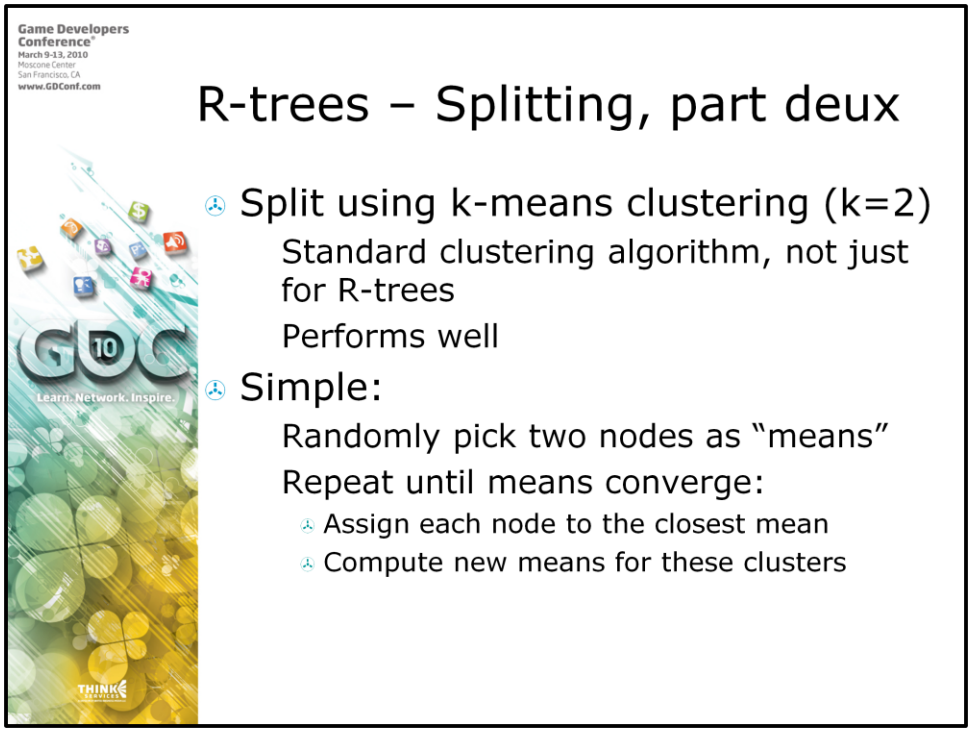
R-trees – Splitting, part deux

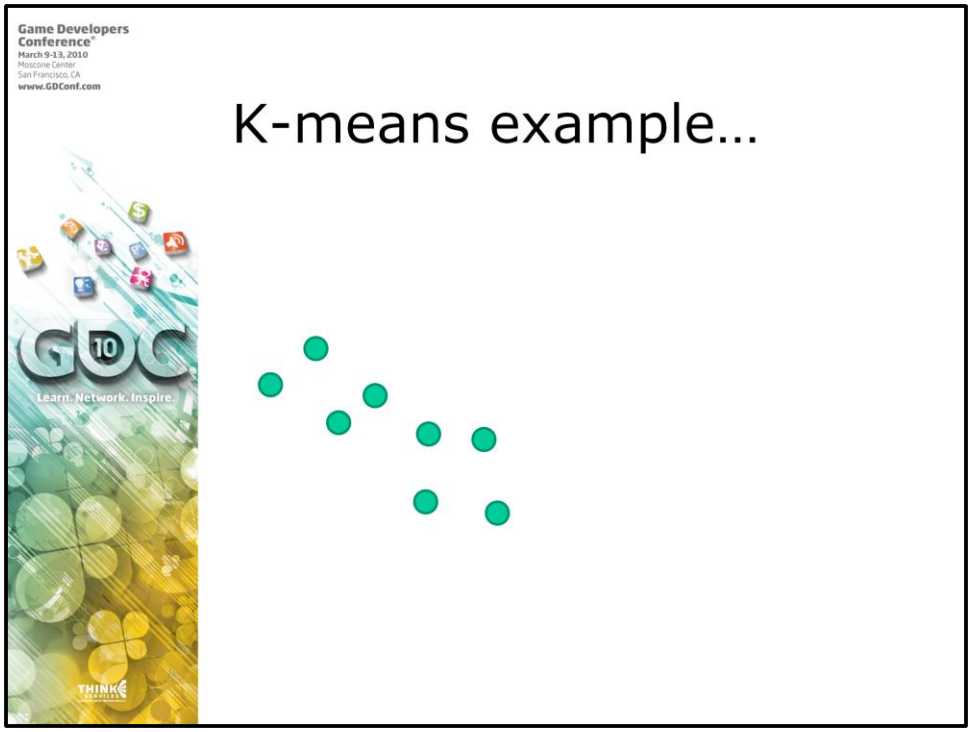
- Due to refinement, splitting strategy isn't *that* crucial
  - Even if we slightly screw up the first time through, we get multiple chances to fix it
- However, must ensure "diagonal" clusters work well
  - Incremental refinement algorithm generates these situations
  - E.g. Ang/Tan splitting method doesn't handle this well (splits along coordinate axes)





See:
Revisiting R-tree Construction Principles
Sotiris Brakatsoulas, Dieter Pfoser, and Yannis Theodoridis

For more on using k-means as the splitting algorithm, though this paper splits in >2 parts, we don't need to do that – the incremental refinement fixes up flaws better.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K-means example…
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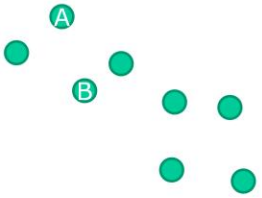
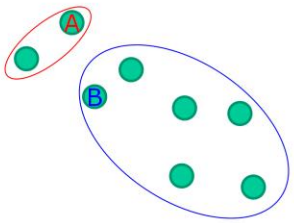
K-means example…

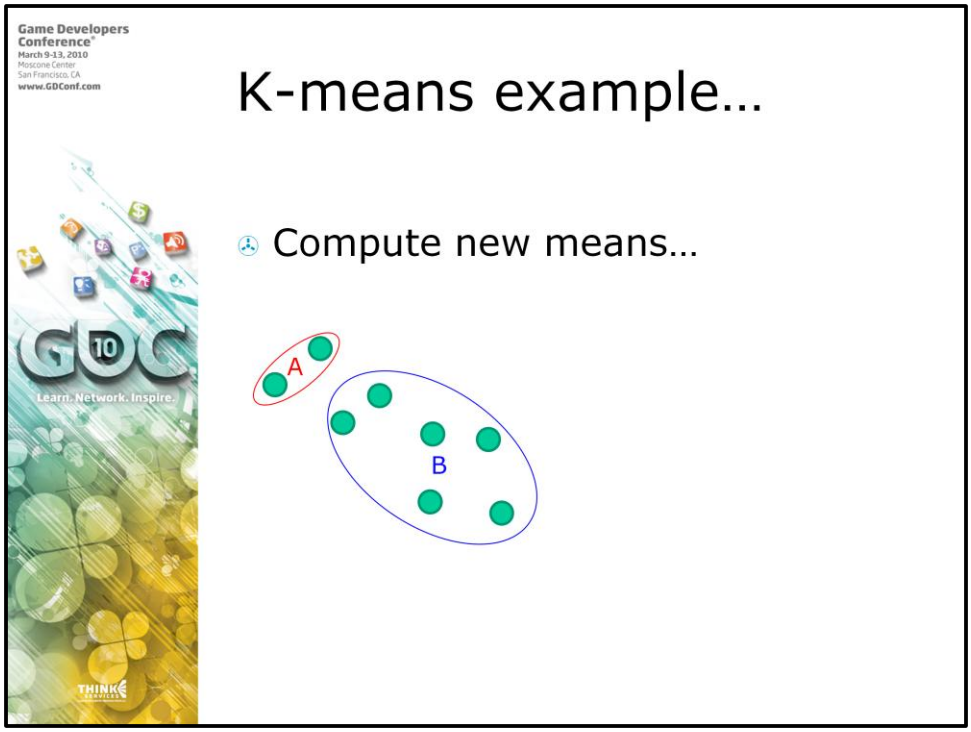
- Pick two seed objects, A and B, at random…



K-means example…

- Classify objects by closest mean…

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K-means example…
Compute new means…
A
B
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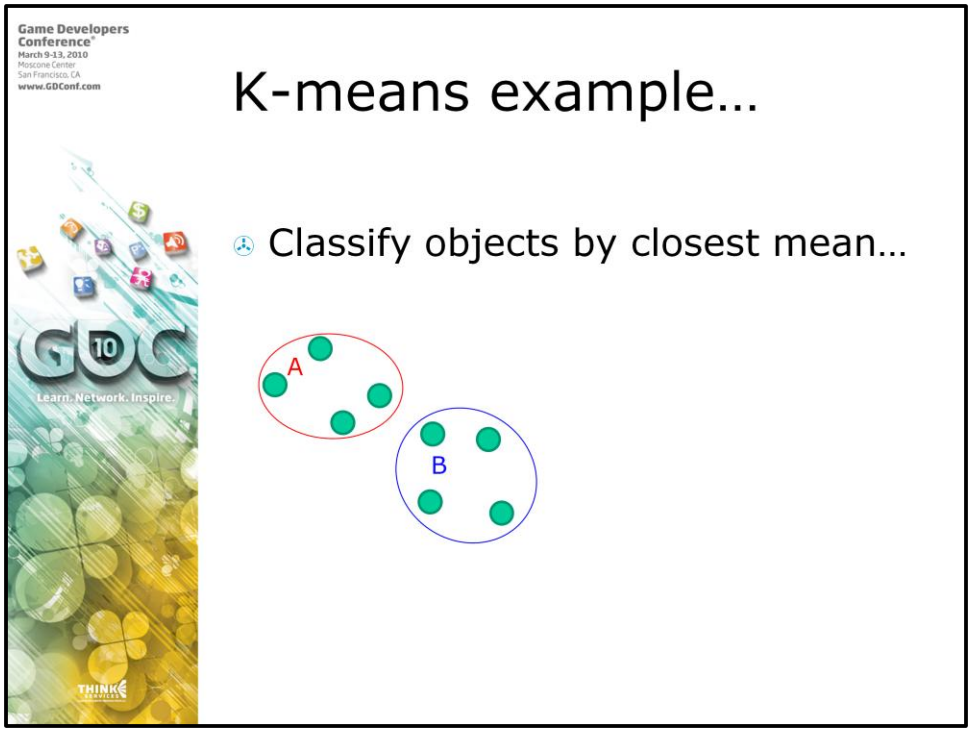
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Classify objects by closest mean…
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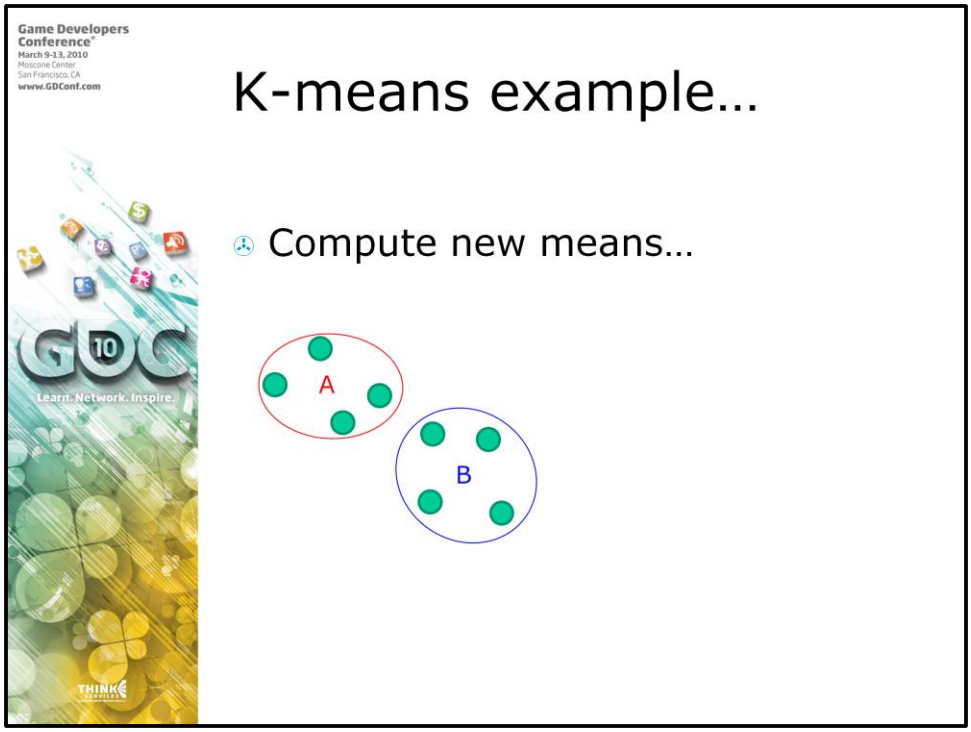
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Compute new means…
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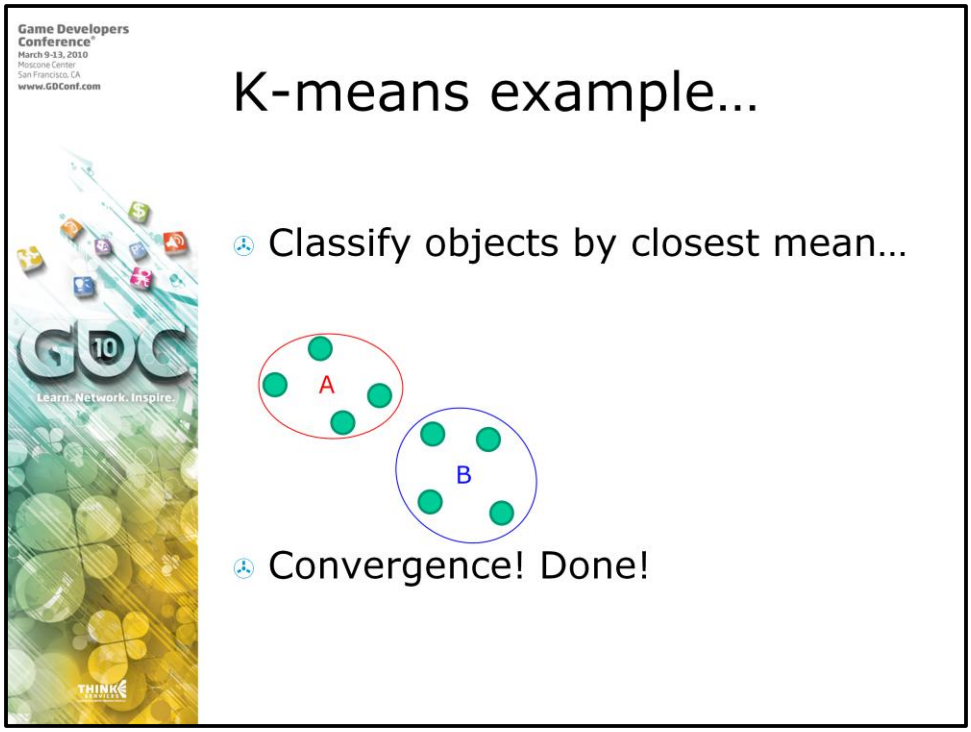
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K-means example…
Classify objects by closest mean…
A
B
Convergence! Done!
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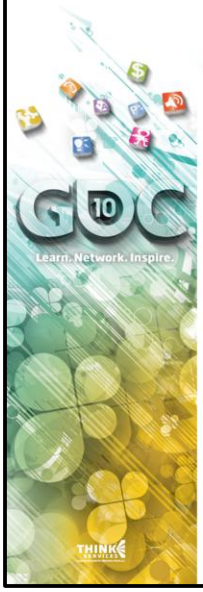
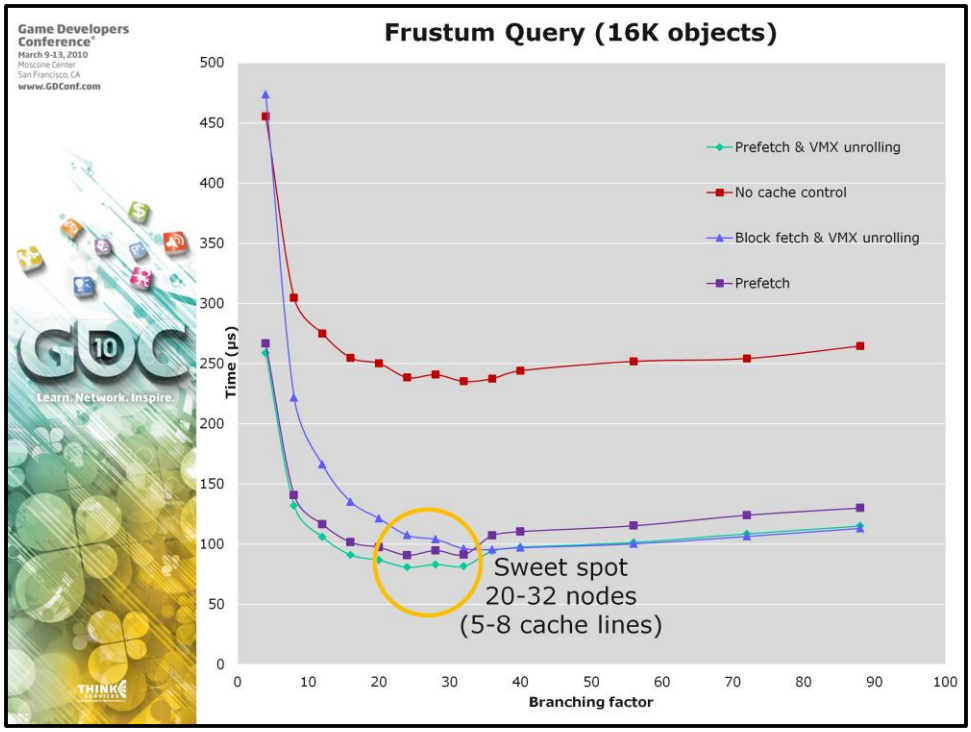
R-trees – Splitting, part deux



- Adapt k-means for AABBs instead of points
  - Need to define what "distance" and "mean" means for AABBs
    - Let "distance to mean" be the diagonal of the minimal AABB that includes both the box and the mean
      - Gives a reasonable estimate of dissimilarity
    - Let "mean of a cluster" be the "center of gravity"



From the very sharp initial drop we should **NOT** conclude that merely increasing the branching factor will yield incredible performance benefits, rather we should conclude that the R-tree algorithm performs poorly at low branching factors. This makes perfect sense when you think about it, as the condition of the R-tree is largely determined by the splitting strategy's ability to perform a "good" split of *all* the objects in the subtree at a given node by only dealing with the immediate children. For very low branching factors (e.g. 4) the immediate children are unlikely to provide sufficient information about the "shape" of objects under the node. Once we reach branching factors of 20-24 though, it's much more likely that the distribution of the immediate children is a good representation of the overall distribution of objects in that subtree, which means that a good split of the immediate children is likely to be a good split of the entire sub tree under the node in question.

The main thing to take home from the graph is the large jump between the curve with no cache control, and the other curves.

Note the jump of the "All optimizaions" line when you go from 8 to 9 cache lines. That's because if you try to issue 9 dcbt's the CPU will stall for the first 8, meaning it can't proceed and work the current node (hiding the fetch latency). This effectively disables pre-fetching. In the real world there may be other things putting pressure on memory, so it may be wise to use only 7 or perhaps 6 cache lines to leave some room for other threads to read form memory.

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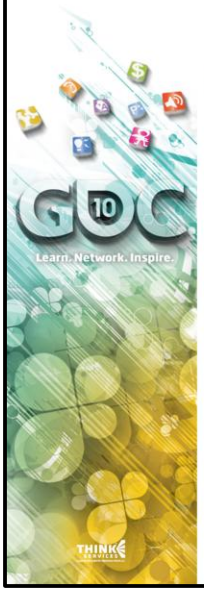
R-trees summary



- Fast, block-based, AABB trees
  - With all the usual benefits of hierarchical trees
- Very cache-friendly
- SIMD friendly
- No "bulk loading" required
- Lots of prior work to exploit

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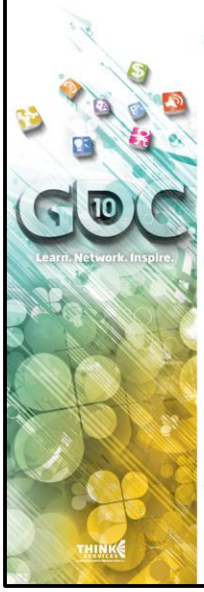

A Reusable Strategy?

- Have problems with cache misses?
  - Has similar been done in an out-of-core scenario?
  - Steal it! Replace "disk block" with "memory block"
    - Use dcbt and dcbz128 on these memory blocks!
- R-trees: my first attempt at this
  - Wanted cache-friendly spatial index
  - Figured it would be block-based, but knew no details
  - Deliberately looked up how database people do it
- I hope this strategy will work again in the future!


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Questions?
Contact: ssylvan@rare.co.uk
GDC 10
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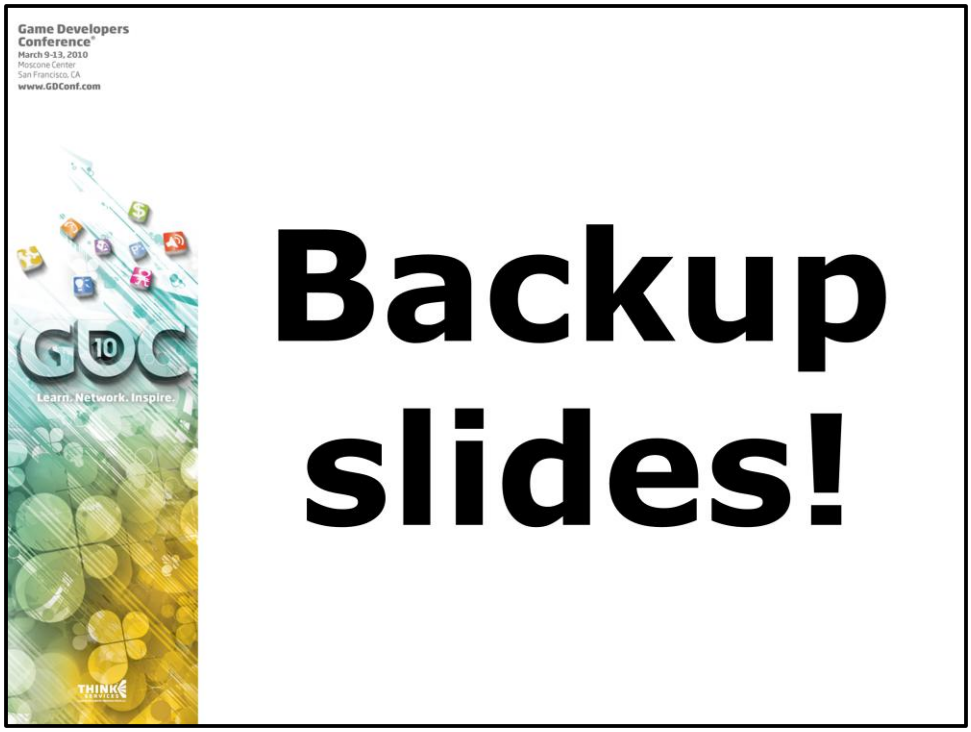
Tons of papers on this, here are two overviews as a starting point:
R-trees: Theory and Applications
Manolopoulus, Nanopoulos, Padapoulos, Theodoridis; Springer 2006
Multidimensional and Metric Data Structures
H. Samet; Morgan Kaufman Publishers, 2006
The original paper:
R-Trees: a Dynamic Index Structure for Spatial Searching
A. Guttman; Proceedings ACM SIGMOD, pp. 47-57, 1984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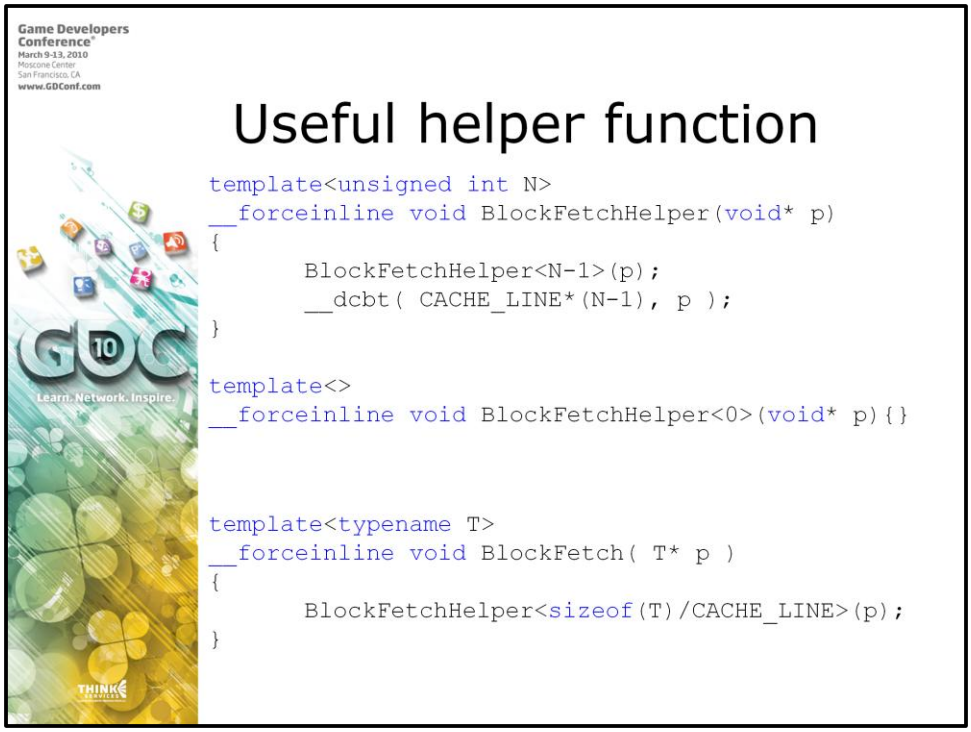
Future work

- Compress nodes, reduce memory/cache usage
  - May lead to too high branching factor?
  - May be slower due to decompression into VMX vectors…
  - Node size can be smaller – just fetch several nodes at a time. This is an advantage over out-of-core techniques. We only need our blocks to be piecewise contiguous.
- Other BVs
  - Maybe spheres.. Maybe 8-DOP… Maybe have different BVs at leafs vs nodes?
- Implement on GPU
  - Very small cache. Even more dependent on good cache behaviour
  - Each ALU lane could do one AABB, we may not need hacks like "packet tracing" to get good SIMD performance
- Spatial joins
  - Usually not considered a standard tool for game applications
  - But this is bread and butter for DB people so it's natural to come across it if you're reading R-tree literature
  - Makes many O(n log n) operations O($\log^2 n$)
- More benchmarks/comparisons (e.g. hgrid etc.?)



The function BlockFetch inserts the required number of dcbt calls for a given value through some recursive template metaprogramming. Same trick works for dcbz128.